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On The Occurrence Of Mud-Debris Flow

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This paper is concerned with the phenomenon of mud-debris flow attributable to the flow of deposits in a valley. The author points out that mud-debris flow is due to the difference of the gradient of sediment deposited by the action of mass force and by the action of the surface stream. For the threshold condition of large rocks, the influence of high concentration of clay particles in a stream and the influence of the differences in water level at both sides of a rock, are also discussed in this paper.

1. Introduction

In Japan regional mountain disasters are often caused by heavy rains, there are especially, many cases in which villages on a fan or talus are destroyed by the unusual mud-debris flow. However, such questions as "what is the mud-debris flow?", "how does it occur?", "how does it act?" cannot be sufficiently explained since these questions involve many factors still unknown, This also means that it is uncertain whether or not the countermeasures now being taken will prove to be sufficient.

The reason for such insufficiency in research on mud-debris flow and countermeasures is thought to be the indistinctness of the actual conditions of mud-debris flow.

Because the outbreak of a mud-debris flow usually takes place in mountainous regions and its occurrence is unexpected, we can very rarely have a chance of observing it. We can only make various conjectures upon the conditions of a mud-debris flow from the results after it has occurred . It seems that this conjecture work is not always appropriate as it does not go beyond past experiences. For this reason the definition of a mud-debris flow is not sufficiently established and the current situation is that interpretations vary among different observers. Therefore in studying mud-debris flow it is necessary to clarify actual conditions and to give a clear and accurate definition.

To cope with the âbove problems in this report, the actual conditions of mud-debris flow will be studied by means of on the spot investigations and studies of past records, both of which will be arranged in order. In addition. dynamical classification of the movements of sediments in mountain regions will be made in order to clarify the domain of mud-debris flow. A fundamental elements in studying structures producing mud-debris flow is the prediction of the place, time and scale of the occurrence.

Prediction of the place varies according to causes, but it is common that mud-debris flow is produced by either volcanic eruption or landslide. For mud-debris flow attended by a fall, prediction of the fall is required and for this we do have a number of investigation. Here comes the theme to be dealt with, that is a knowledge determined by topographical research of the place producing mud-debris flow through the movement of deposits in a valley .

The time and scale would naturally be known if the acting structure were clarified. Regarding the development of mud-debris flow, excepting special instances, we may refer to Tani's[1] classification that 1) Mud-debris flow produced by fallen sediments; 2) Mud-debris flow produced by the collapse of a natural dam formed by fallen sediments; 3) Mud-debris flow into which the sediments deposited in a valley bed moved and developed. The above 1) and 2) are understandable in a way, but there are many points incomprehensible in the structure of forming mud-debris flow in category 3). This study therefore, shall be directed here.

In discussing mud-debris flow, an indispensable item is the movement of a big stone attending the mud-debris flow. In the movement of a stone, there are two conditions to consider, namely, the condition in which a stone sinks perfectly into a steady flowing stream, the other, that of a stone moving in a sweeping condition in the surge in front of the mud-debris flow. In the former case, the conventional equation of critical tractive force in the case of a clear stream is applicable and so mention will only be made here concerning the equation of critical tractive force in the case of a mud stream.Consideration will then be made concerning the critical movement of a stone by a surge front.

2. Realities of Mud-Debris Flow and Its Definition

2.1 Realities of Mud-Debris Flow.

(1) Realities of actual mue-debris flow and those of recorded investigations. Although the first thing to do should be to start with a definition of mud-debris flow, it shall be touched on after having studied the realities of the phenomenon known as mud-debris flow and having arranged them, as the realities have not yet been cleared up as mentioned under the title of the Introduction.

Tani[1] clasified mud-debris flow into 3 types as mentioned in the Introduction. R. P. Sharp[2] and C. F. S. Sharpe[3] classified flow into Semiarid, Alpain and the Volcanic type. At this stage, according to the causes for supplying sediments to a place of flowing water, classification is as follows: Mud-debris flow caused by volcanic eruption, fall from a mountain side, flow of deposit in a valley, and landslide. Subsequently, their characteristics are as follows.

1) Mud-debris flow caused by volcanic eruption.

In the mud-debris flow arising from a volcanic eruption, there is a direct outflow of eruptions and an outflow of the deposit of volcanic ash on a mountainside by rainfall. The former is known as a lava flow or volcanic mud flow, but the frequency of this phenomenon is not high. The latter sometimes occures and instances are not infrequent.

(a) Mt. Tokachi[4]: The mud-debris flow which occurred at Mt. Tokachi in 1926 was not mud-debris flow caused by the direct outflow of the collapse of the eruption but was flow caused by water produced by the snow which had melted from the eruption falls, eroding the sediments on the hillside and procuding a mud-debris flow; this however an exceptional case. The snow at the time was 0.5 m–1.5 m deep, or, in other words, 30% of it turned to water. It would easily be predicted that if the slope, usually free from the action of water flow, has suddenly to carry this amount of water, it would suffer sudden erosion. The velocity of the flow was 40 m/sec, at the place of occurence, and 2.9 m/sec, at the place near the region of the deposit. The diameters of sediments that created the mud-debris flow are shown in Fig. 2.1.

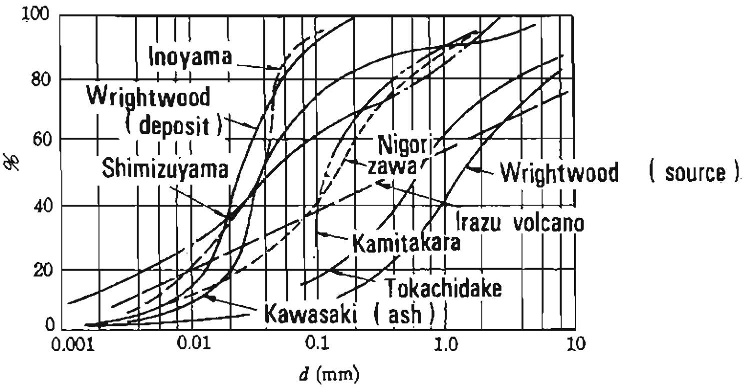

Fig. 2.1 Particle size distribution for deposits of mud-debris flow

(b) Mt. Yake: At Mt. Yake, which created the Taisho pond through mud-flow during the eruption of 1915, a subsequent mud-flow was produced each time a small scale eruption occurred. One such eruption took place in Sept. 1962. Rain falls of only 5 mm that started on the subsequent day transferred ashes into a mud-debris flow each time it rained. The bottom of the river channel was excavated causing damage to the river structures. This meant that the ashes covering the mountainside were unstable and prevented the permeation of rain-water easily transferring themselves into mud-flow. In 1968, Mt. Yake had a rainfall of 26 mm a day which created a small scale mud-debris flow into the Ashiarai valley in Gifu Pref. piling up a long line of innumerable stones the size of about 1 mm on both sides of the river channel, as shown in Fig. 2.2.

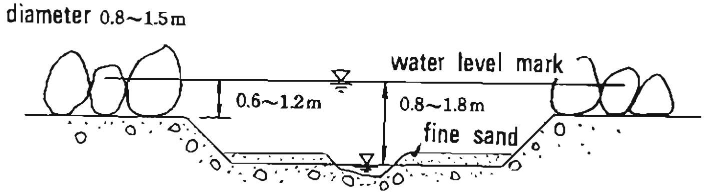

Fig. 2.2 Cross section after mud-debris flow threw in Ashiaraidani valley

(c) The Irazu Volcano[5] located at the center of the Republic of Costa Rica. From Mar. 1963 to Mar. 1965, this volcano underwent a period of violent activity, erupting millions of tons of ash. This ash caused a hydrological unbalance in the stream which began to produce a large flood charged with volcanic ash and debris.

According to records, the Reventado river flooded the city of Cartago 5 times during the 240 years prior to 1963. The flood of 1951 was caused by a storm with a precipitation of 154 mm in 24 hours. This flood had a return period of approximately 50 years.

After ash eruptions, the rain recorded was only 24.4 mm a day, but the flood was one of the largest for this river. During the rainy seasons of 1963 and 1964, five mud floods exceeded the peak discharge of the 1951 flood. In 1964, nineteen floods exceeded 3 m of the peak stage mentioned above. The major floods of 1964 have concentrations to 770.000 ppm. The specific gravity of mud flow ranged from 1.2 to 1.9. The floods are able to transport large rocks, some about 5 m in diameter.

2) Mud-debris flow attributable to falls from steep slopes on a valley side.

The fall attended by heavy rain is due to water flowing out from a slope. Many of the falls are found at a headwall in a valley or at a place directly facing the channel. Where the soil consistes of weathered sediments, the soil is rich in granule and is mixable with the stream to be unified.

(a) Mt. Tsukuba[6]: It was in July 1938, that the headwall in the valley collapsed after the long rain which ran for one full month. There were 14 mud-debris flows in one hour, out of which 8 had a mixture of stones, 5 contained only stones, and the remaining 1 was of only mud water. The grade was 45° at the point of occurrence, 9° at the point of deposit, and the velocity was 2 m/sec.

(b) The Mayflower Canyon[7]: In August, 1961, a mud-debris flow occurred from a talus having the grades 35°–41° of the Mayflower Canyon, southwest of Denver, flowed down to be deposited at a place of grades 7.5°–12°. The place of the occurrence was a talus bed of over 4 m thickness. The rainfall on the privious day was 290mm and 245mm on the day of occurrence. The velocity was 15m/sec. ar the center and 1 m/min. at the point near the deposit. It was observed that there was a difference in velocity between the stream and grains. The stream involved big stones the size of about 0.8 m which, however, were exclusively in front of the surge. Assuming that the stream was laminar flow, the coefficent of viscosity was calculated to $\mu=3\times10^4$ poises. From the growth of lichen species at the deposit area it was inferred that mud-debris flow had occurred once in 150–400 years.

3) Mud-debris flow attributable to the flow of deposit in a valley.

From among those that are generally known as mud-debris flow, many cases belong to this category, they occur due to the erosion of the bed and base of a valley, irrespective of collapse of the slope.

(a) Wrightwood[8]: The mud-debris flow which occurred at Wrightwood, Calif, was the outflow of the deposit at the headwall in a valley due to thaw. The grades at the point of occurrence were 32°–24°, and the soil was rich in viscosity and fineness. The stream water in a state of soup type concrete ran making a surge at intervals of several seconds or several minutes. Where the stream channel was limited, rolling pebbles gathered and ran ahead. The apparent density of the stream was 2.4. 75%–60% of sediment was contained. Despite the appearance of high liquidity of the stream, it had so high a viscosity that it would not spray even if a stone were thrown into it. Having taken it for a laminar flow, the coefficent of viscosity was $2.1\times10)$ poises. After the stream ran 24km, it left the deposit at the slope of a grade of about 1°.

(b) Mt. Akagi[9]: The mud-debris flow aroused by typhoon "Catherine" in 1947 was conspicuous in each of the two tributaries of the Numao river, the Maeiri valley and the Ushiroiri valley. A large scale mud-debris flow occurred in the former valley which usually carries a scanty water flow: It is inferred that the deposit was big due to lack of running water. In fact, the former river seems to have been earlier in restoring the alluvial sands lost by the mud-debris flow than the latter.

(c) Ashiwada Village, Yamanashi Pref. : A mud-debris flow was brought about by typhoon No. 29 in September, 1966. Although there were a fair nubmer of falls at the mountainside, almost all of them were below the slopes moving no further down. What flowed out as mud-debris flow were the sediments that had accumlated behind the narrow part in mid-stream. Regarding this, mention will be made again in 3).

(d) Yasuda Village, Nigata Pref.: The mud-bedris flow which occurred in 1967 was also the runoff of the sediments accumulated in the valley and had little relation with collapse. At the valley head, there was a bed rock that was an crop out of considerable length. This mud-debris flow destroyed an erosion control dam part of which, in the dimensions of 10 m×4 m×2 m was transferred to a distance of 800 m.

(e) Kushida Valley, Miye Pref.: A mud-debris flow took place on the slope of the headwall in a valley. Debris accumulating on the land surface dur to frost columns flowed out during the rainy season. The crashed rock debris mixed with clayey soil flowed down swelling. During the period from 1965 to 1967 mud-debris flow occurred 20 times.

4) Mud-debris Flow attributable to Landslide.

Speaking of geological features, the deposit tends to have a fluidity to which the incentive is water. However, there is not always the relation between mud-debris flow and rain.

(a) Ura River, Nagano Pref.: This river is one of the branchs of the River Hime. The geology is of a volcanic soil having much viscosity. Sediments driven into the river channel through landsliding are very viscous.

(b) Nakanosawa valley, Nagano Pref.: The valley is situated opposite the River Ura. The viscous soil has accumlated to a thickness of 7–8 m as in the river Ura. In the thawing season landslides and subsequent gradual flowing down-stream are produced . Some, as with the River Ura, frequency of occurrence is extremely high.

(2) Characteristics of Mud-debris Flow.

Recaptulation of the characteristics of mud-debris flow of which mention has been made above is shown in Table 2.1 below.

The synthesis of the characteristics of mud-debris flow is as follows:

Table 2.1. Characteristics of Mud-debris Flow in the past.

Location	Velocity	Source area	Deposit area grade	Density of fluid	Average diameter
	(m/sec.)			(t/m))	(mm)
Mt. Tokachi	40 –2.9	—	—		0.6
Irazu Volcano	—	30°–36°	—	1.2–1.9	0.3
Mt. Tsukuba	2.0	30°	9°	—	—
Mayflower	15 –2.5	35°–41°	—	2.53	—
Nakanosawa velley	0.5	10°	—	—	0.045
Mt. Yakedake	—	—	—	1.5	0.12
Ashiwada village	—	20°–30°	below 10°	—	—

Wrightwood	0.3–4.6	24°	4°–1°	2.4	1.5 (Source area)
Nigorisawa valley	9.0	—	—	1.2–1.5	0.15
River Ura	6.0	20°	—	1.61	0.04
Mt. Akagi	1 –2	—	—		

1) Grain size of Mud-debris Flow

The grain size of mud-debris flow is not large and there are manys case in wihch the so-called "mud-debris flow" would be better defined as "mud flow".

2) Characteristics of Mud-debris Flow.

That the spearhead of a mud-debris flow swells as it flow down is a fact every observer of mud-debris flow unanimously acknowledges. Kawaguchi[9] and others quoted from the report of Shrumberger on the result of his observation made on the flow of the mud-debris flows in the Alps. It says, "The mud stream coming down a ravine has little indication of having any fluidity, and is in a state as if it were an amalgam consisting of soil and various matters. When it contains much soil giving an appearance of being solidified, rocks as large as 5–6 m^3 are carried forward as the advanced guards. Fig. 2–3. The rocks march forward, taking the lead for several minutes, but stop at some obstacle to be then swallowed up by the stream. Then, another rock goes ahead to take the place of the previous one. Continuing this rotation, the mud-debris flow marches on, now rapidly here, then slowly there.

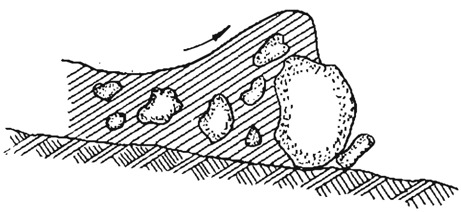

Fig. 2.3 Sketch of longitudinal section through advancing mud-debris surge

After the advanced guard of the huge mass of rock has passed away, the mud flow streames down with a fairly constant speed. It was something black which had nearly no fluidity and simply looked like a muddy object with little water component. It seemed to be nothing but large muddy river.

Meanwhile, the water surged on from behind to flow torrentially over the mud-debris flow and finally caught and joined the spearhead of the heavy mud-debris flow to give it a new impellent force while sweeping away the mud flow left in the valley. The scene thus left gave a spectacle as if the valley bed itself deserted its own site along the waterway. A section in the shape of a U was left. There was no trace of mud on the valley bed excepting those showing the height of the mud flow.

The above description seems to give a very correct explanation on the conditions of mud flow, judging from what was observed of the conditions of mud-debris flows occurring at Nigorizawa and Yakedake. The swelling at the head of the mud-debris flow was produced by the difference in resistance due to depth. The fact that the mud water of the flow adds to this nature has been affirmed through analysis and experiments. Interruption by rocks has additional effects.

3) Inertia of mud-debris flow.

Mud-debris flow has a stronger inertia than ordinary flow. For example, it was observed at Mt. Akagi and Ura River that at the bend of the channel bottom there is a difference of 3–4 m in the water level between the inside and outside of the passage. Taking the case of Mt. Yakedade, it was observed at the dam, Kurotani No. 3 situated at the bend in the passage, that zero was nearly the height of the water level marked on the side wall which corresponded to the inner side of the bend, while the mud-debris went over the 2 m high side wall at the outer side which was 10 metres off the inner side. This left us to conclude that the fluid might be fairly viscous.

2.2. Definition of Mud-debris Flow.

(1) Defintions expressed by past investigators.

Touching now on the problem of the definition of a mud-debris flow, the author should like to try to clarify the image of mud-debris flow, such being one of the objects of this paper.

R. Nomitsu[10] et all defined mud-debris flow stating that "the phenomenon in which a substance in a state of gruel containing a conspicuously large volume of sediments against the water volume moving by itself by action of specific gravity on a steep river bed is known as mud-debris flow"

H. Koide[11], dividing the mud-debris flow into mud flow YAMATSUNAMI and mud-debris flow, defined "mud flow as the phenomenon in which the sediments created by the fall of a mountainside are pushed forward into a valley; a stream mainly containing clayey soil, mud-debris flow is the phenomenon in which the deposit of sands and stones in a valley are pushed forward and have on connection with landslide".

T. Kaki[12], separating YAMATSUNAMI from mud-debris flow, stated that YAMATSUNAMI is composed of 70% of soil and 30% of water, and its movement is a pushing forward rather than a flowing, while mud-debris flow is composed of 30% of soil and 70% of water and the water level is not lifted as much". It is especially to get at the kernel of the problem that they pointed out that it is mud flow and flow of the deposit in a valley. In order to get this estableshed it is necessary to decide dynamically the region within which such phenomenon can arise.

(2) Further definition through dynamical examination.

The movement of sediment in a mountainous region is classified according to whether or not distortion is given to matter when acted by force. The result is related to the friction force acting on the boundary surface. When distortion does not appear in the interior of the elements, the friction force is in proportion to normal force on the boundary surface. Also when distortion arises their accumulated value corresponds to the force acting on the boundary surface. This force is usually shown as being in proportion to the force of velocity of the matter. The phenomenon is known as flow.

The above classification is further reclassified according to the relative magnitude of the external force acting on the element surface and the mass force acting on the mass elements. Recaputilation is shown in table 2.2.

Now, what is to be called mud-debris flow according to this table? The word "mud-debris flow" has been used frequently. However sediment flowing out to a

Table 2.2 Kinetic Classification of Sediment Transport in Mountainous Areas.

Existence of distortion in the element	Frictional force on boundary surface	Relative strength between external forces acting boundary surface and mass force	Type of sediment transfer in mountainous areas	Phenomenon
Non existence	Proportional to normal force on boundary surface.	External force acting boundary surface excels the mass force.	Bed load	Bed load on a slow grade Fall of large stone on steep channel →
Motion as a rigid body	Read to be proportional to the power of velocity of the mass	Mass force is greater than the external force on the mass surface.		→ Mud-debris flow
		mass force excels.	Fall	Fall on a slope
			Slide (of stones, debris)	Landslide
Exist. (Motion as fluid)	Proportional to the power of strain rate	General mass force		Stream in which the sediment and water are united in a body. →
	Expressed as proportional to the power of velocity of the mass		Flow	Landslide Creep Motion of stream

channel due to a fall from a slope is not mud-debris flow however carge its volume maybe. The sediment movement in the type of bedload is also distinguished from the mud-debris flow. But in cases when huge stones scattered on the bed of a valley are moved in the water depth the same as, or smaller than, the size of stone, it cannot but be called mud-debris flow. No matter how small the grain size of the sediment may be, it is mud-debris inasmuch as it flows in a body even if the scale is small. These two are taken as mud-debris flow in this paper.

The two movements are different to each other in dymanmical domain. The former especially, is transferred by the external force while the latter flows by the mass force. This means that the reality of a mud-debris flow is the fluid in which the sediments adhere to the water and behave as a body. This shows that the transfer of a huge stone is a collateral phenomenon attending to it. Consequently, the critical condition of the two is decided separately.

The critical condition of occurrence can be decided, in a stream in which the sediment and water are united in a body, by the condition of the maximum allowable concentration in a volume. The auto-suspension of Bagnold may be one of the ideas in search of this critical condition.

Regarding the transfer of huge stone, the limitations of rolling of the stone may be the above critical condition. Studuy on this subject will be described in section 4. The dynamical domain of the landslide is the same as that of the mud-debris flow, but one which moves a distance of several centimetres a day is distinguished from mud-debris flow. The limit in this case may be decided by the nature of the composed substances.

3. Formation process of mud-debris flow attributable to the flow of deposit in a valley.

3.1 Transfer of Sediment in a Valley.

The sediment in a valley is not only transported by streams but is also supplied by the fall from the slopes on both sides of a valley and from the fall of the sediment peeled off the land surface through such phenomenon as frost (hereafter called mass transport). At the downstream of a valley where water appears on the deposit surface,

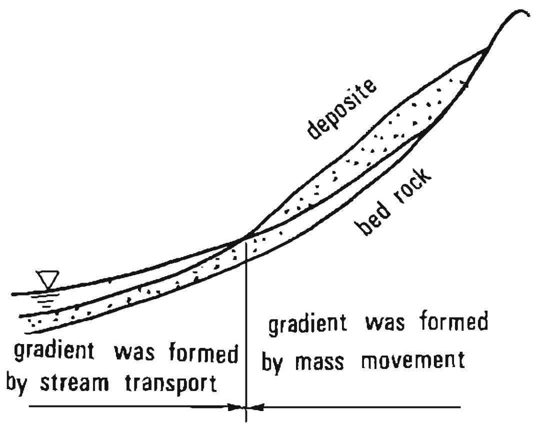

Fig. 3.1 Sketch of gradient in valley

the sediment is transported by stream, and the deposit is made in the state of the force of the stream being balanced with the nature of the sediment. Whereas at the region of the headwaters where the surface stream is lost, the sediment supplied by mass transport accumulates as it is without being carried down stream. There exists in a valley a boundary in this sort of structure of transport, though such a boundary can not be located distinctly. By the balanced forces of the two structures of transport, the boundary moves upstream and down-stream. Where the surface soil is thin and the mass transport is weak, the predominance is stream transport near the summitand the accumulation of sediment is small. However, it can be said that in a zone strongly weathered or in a uncongealed zone of eruption where the supply of sediment is plentiful, the boundary is brought downward and the deposit advances behind the boundary.

3.2 Difference in the Deposit Gradient according to the type of Transportation.

The gradient of the deposit tells the history of the transport of the sediment carried there. The gradient of deposit of the sediment carried by stream (hereafter called aqueous grade) varies according to the velocity of the stream and the grain size distribution. An experiment in regard to the steepest gradient that was unaffectedly made by water when water runs over the sediment layer was conducted by the author. The result showed that, within the limit of the water depth being from one to three times the grain sized, the approximate value was 13° as shown in Fig. 3.2. in which the numerical value indicates the value of $u_{*_c}{}^2/u_*{}^2$ of each experimental value. On the other hand, the gradient of the deposit of the sediment brought by mass transport is to have the grade regulated by the internal friction angle of the sediment. This is much steeper than the queous grade, and it cannot withhold when acted upon by a running stream.

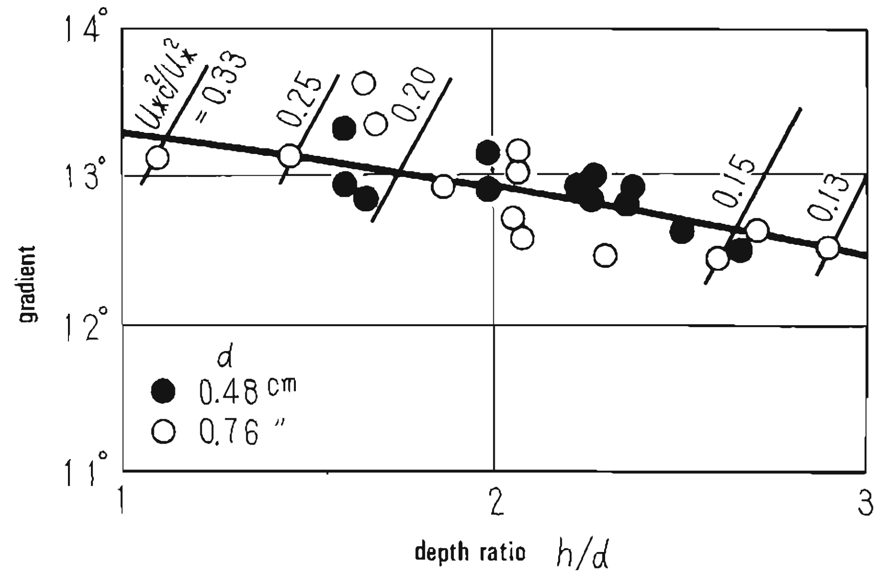

Fig. 3.2 Experimental result of maximum gradient was formed by stream transport

3.3 Formation Process of Mud-debris Flow Attributable to the Flow of Deposit in a Valley.

Under heavy rain the region of the surface stream expands toward the up-stream and the boundary point shifts up-stream. The result is that the deposit which has accumulated by the action of mass force but which has not hitherto been acted upon by a stream are transferred by the action of the surface stream to an aqueous gradient. The movement of sediments disposed with this change of circumstance could be called mud-debris flow.

3.4 Comparison with Actual Phenomenon.[13]

There was a heavy rain in and aroud Ashiwada Village, Yamanashi Pref. in September, 1966, when the run-off of a large amount of the sediments took place. This was almost all of the deposit in the valley with no participation of the fall in the mountainslope. Fig. 3.3 shows the classification of the topographic features at equivalent gradient, and Fig. 3.4 shows the area where scours and deposits took place in September, 1966. Comparison between Fig. 3.3 and Fig. 3.4 indicates

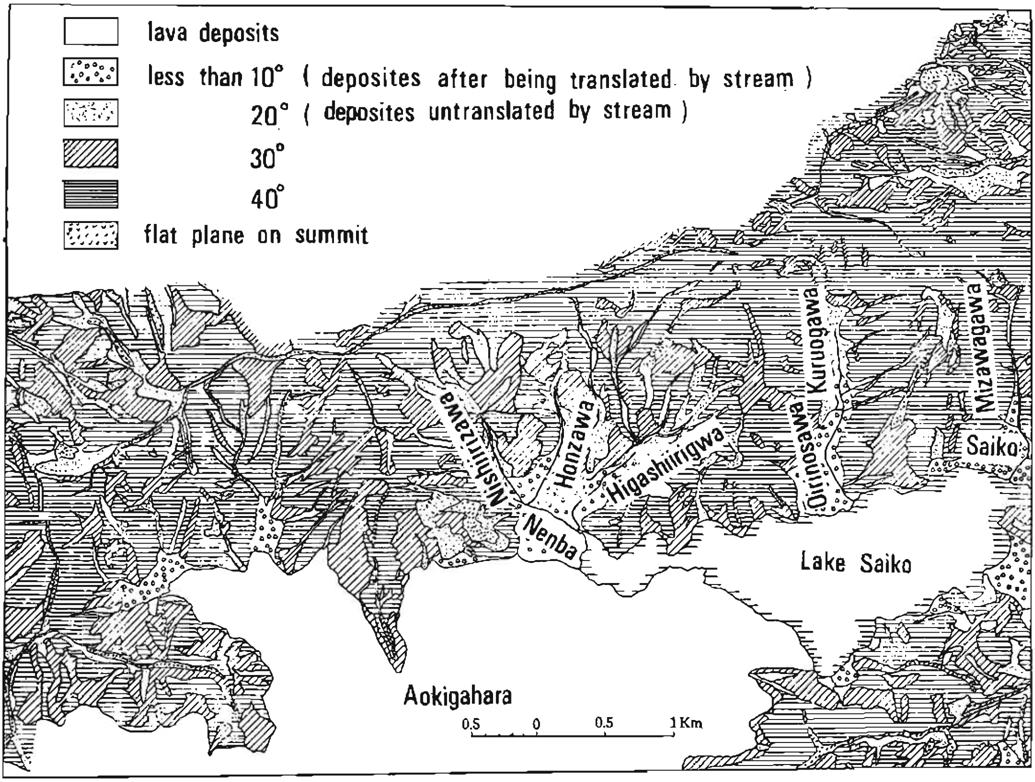

Fig. 3.3 Identical gradient map (Asiwada village)

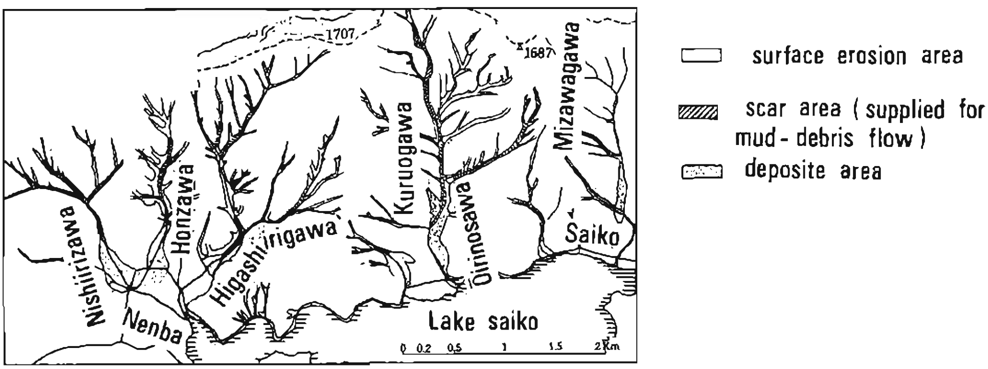

Fig. 3.4 Sediment movement by heavy rain (Asiwada village)

that the fall in the slope is limited within places having the numerical value of 30° for the gradient, 20° for the scour and 10° for the deposit. The distribution of the occurrence coincides well with that of the equivalent gradient map. Places having a gradient of 20° have a nature resembling a talus, the deposits having such a mixture of soil as afforestation was at work, which seems to have suffered from no sift from water flow. From the traces of flowing water over the deposit, it is inferred that water ran over the deposit brought by the mass transport and induced the run-off of the large quantity of the sediments in the process of shifting to the queous gradient.

Considering it in this way, the volume of the deposit in a valley that has not suffered any sift of water flow comes to have a relation with the scale of mud-debris flow. As to this deposit in the nieghbourhood of Ashiwada Village with reference to the topographic map, the biggest was Nishiirizawa followed by Motozawa and Misawa river in that order of size: The sediment discharge investigated by the prefectural government was in the same order verifying this inference.

As the deposit is small in the areas outside the nieghbourhood of Ashiwada village which is inclued in the Fig. 3.3, it is understandable that there was no large mud-debris flow in those outer areas insomuch as Fig. 3.3 shows.

In the mud-debris flow which occurred in August, 1970, at the two valleys, Kamihorizawa and Kamikamihorizawa, the gradient at the points of occurrence ranged from 18° to 23°, showing a similar numerical value.

Fig. 3.5 is for the lateral change of the bed elevation before and after the occurrence of the mud-debris flow in the valleys around Ashiwada village, and Fig. 3.6 for the longitudinal change in the bed elevation taken from Fig. 3.5 At the positions of both of the two channel bottoms in Fig. 3.6 where the old-time gradients were bigger than the aqueous gradient, it is observed that the grades have been getting slower.

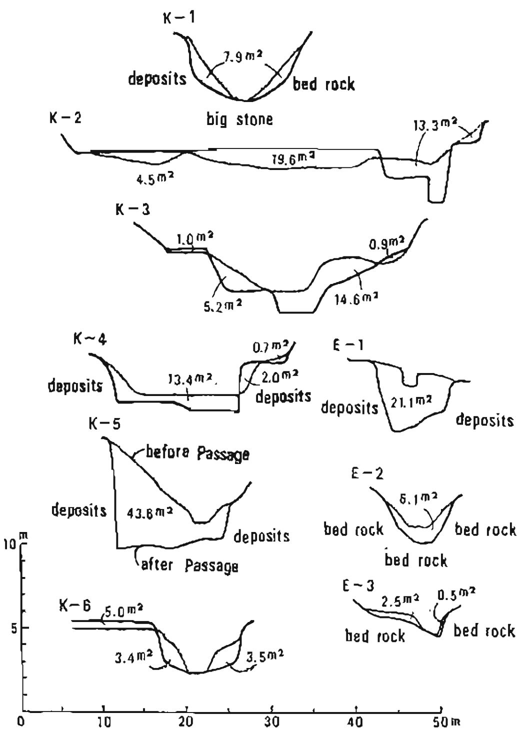

Fig. 3.5(a) Lateral variation of bed elevation by mud-debris flow (Ashiwada village)

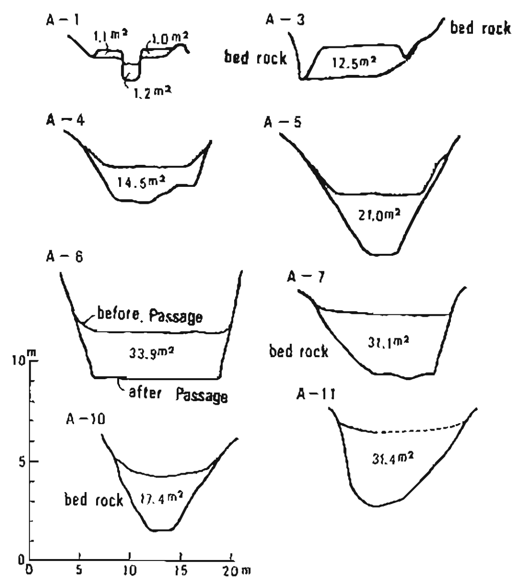

Fig. 3.5(b) Lateral variation of bed elevation by mud-debris flow (Mizawagawa)

This is the fact that would verify what was mentioned above. It is one of the characteristics frequently observed in mud-debris flow that the gradient is uniformly mitigated to the lateral direction unless there is a bed rock or a big rock as shown in Fig. 3.5 In August, 1969, mud-debris flow occurred in each of the Taruzawa and Rokazawa valleys, both running at the upper reaches of the River Kurobe. Fig. 3.6 shows the change of the bed elevation in both valleys before and after the mud-debris flow. It took the same form entirely as in the area surrounding Ashiwada village. In view of this the depth of the deposit in a valley is bigger that expected.

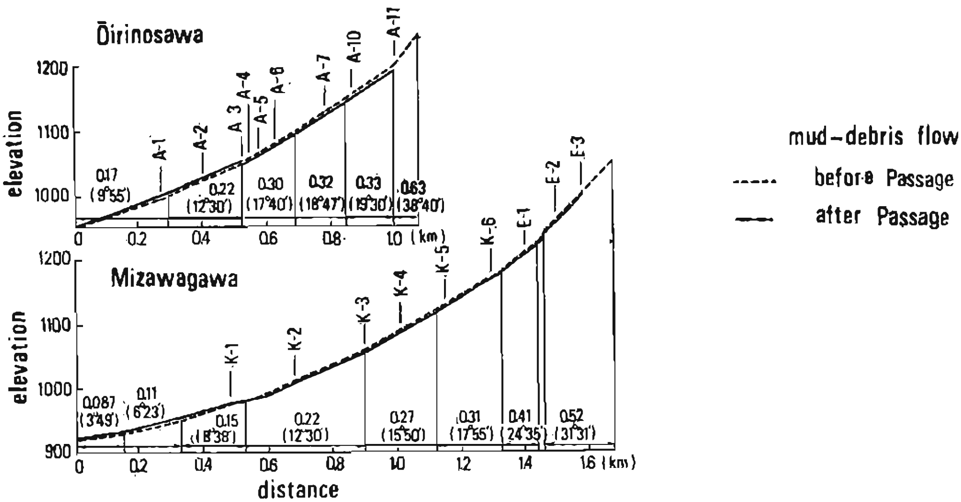

Fig. 3.6 Longitudinal variation of bed elevation by mud-debris flow (Ashiwada village)

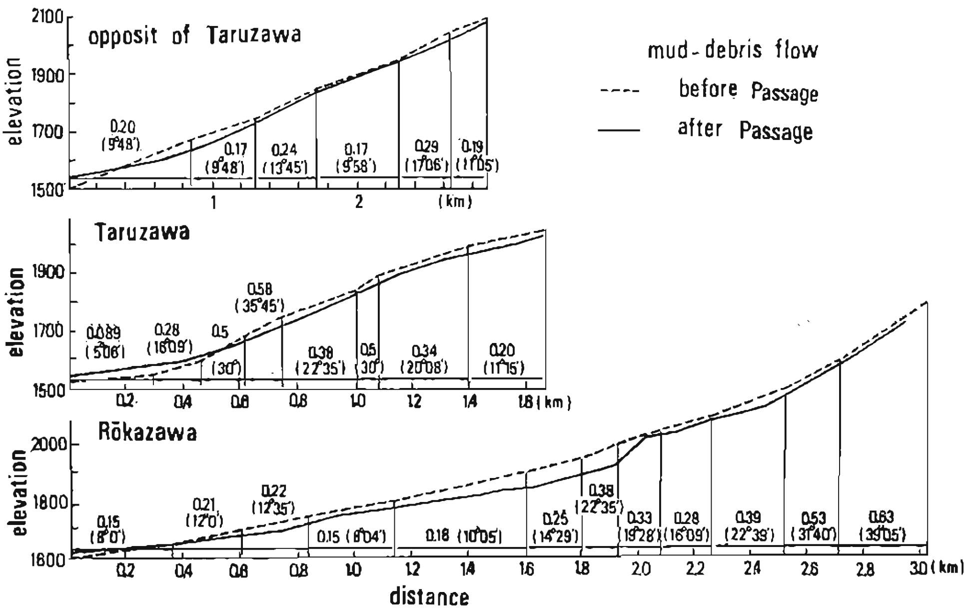

Fig. 3.7 Longitudinal variation of bed elevation by mud-debris flow (Kurobe River)

The extent of lowering the river bed in the duration of a mud-debris flow relates to the depth of the original deposit and the duration of mud-debris flow. It is assumed that the gradient is reduced to the aqueous gradient when the depth of the deposit and the duration are sufficient.

Mud-debris flow born on an extent having a gradient below the aqueous gradient is transformed rapidly into a stream having sediment and water separately. Even if the stream still carries a large amount of sediment, the change of the river bed of the extent is dealt with as the change due to the bed load transport. As, in this extent, the transport capacity of the channel bottom is smaller than the sediment discharge brought by the stream from the upper reach, a deposit is always made. This is the reason why the deposit shown in each of Fig. 3.6 and the Fig. 3.7 is made on the original river bed having a gradient below 10°.

3.5 Rainfall Necessary for Occurrence of Mud-Ddbris Flow.

In the above consideration, the mud-debris flow arises when the surface flow runs over a deposit having a gradient bigger than the aqueous gradient. Consequently, the rainfall required to create mud-debris flow is the rainfall required to create the surface flow over the deposit. There are two forms of incentive to the surface flow, one is that the deposit is perfectly saturated with the infiltrated water and the other is that the rainfall intensity exceeds the infiltration. However, judging from the records of rainfalls each time mud-debris occurred, the mud-debris does not occur in the latter case but flow takes place only when the surface flow is created by rainfall of high intensity falling after the antecedent precipitation saturated the deposit.

3.6 Process of transformation of the deposit into a mud-debris flow.

When the mass transport makes the surface flow run over the deposit, the gradient of the deposit is transformed into aqueous gradient according to the discharge and the grain size, irrespective of the initial gradient. At this stage it is not the whole body of the slope that gradually takes the transformation but the part of it where the surface flow develops which immediately turns to an aqueous gradient. The surplus sands released by the transformation of the gradient are sent on to the river bed down-stream which will only afterwards have the surface flow to create a dune. The surface flow that is only on the up-stream side of the dune piles it up further down-stream and the dune gradually develops moving down-stream. In the domain where a dune has a steep gradient, the movement of the dune is quick with a velocity approximately the same as that of the surface flow. The state of the development of a dune in experiments is shown in Fig. 3.8.

The dune would have an overflow at the place where there is a change in the width of the channel or in the depth of the deposit layer, and induce a result the same as that of the collapse of a dam. In some cases deep slides would appear in the sand layer while the dune moves. The dune itself is further fluidized by mixing with water.

It is generally said that the cause producing a mud-debris flow is the failure of the natural dam formed in a stream. The same phenomenon arises when the surface flow acts on a deposit having a gradient exceeding the aqueous gradient. This phenomenon makes it easier to get the sediment and water unifieid, and yet even without so big a tractive force the sediment and water could be unified with the quantity of water that any valley occasiohally supplies

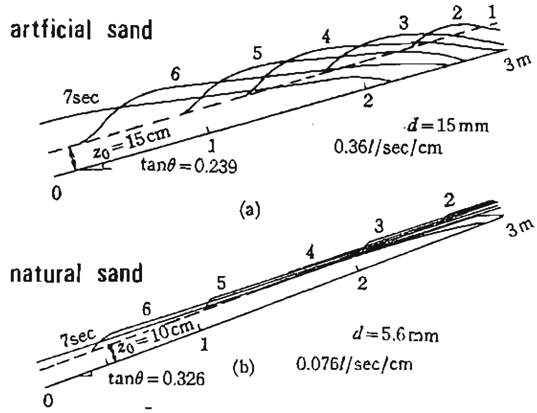

Fig. 3.8 State of growing on sand dune

4. Critical Condition of Rock Movement

In the motion of sediments in a valley as mentioned above, there are a) the slide or creep of the deposit and b) the motion which reduces the gradient of the deposit.

Big rocks may be transferred through these processes, but these processes occur at places where the gradient is over the soil mechanical stability for the above a), and where the gradient is over 13° for the above b), against which, however, the transfer of a large rock so far observed arose in a gentle solpe having a gradient below them, e.g., from 6° to 10°. Therefore, it is thought, that at such a comparatively gentle solpe the water flow escapes from a rock and transfer of a rock takes the form of bed load. And yet in many cases, the water depth was about the same or even less than the diameter of the rock. In view of this, the factors conducive to the transfer of rocks can be enumerated as follows.

(a) Influence of a fluid containing an abundance of clayey particles.

(b) Influence of the difference in water level at both sides downstream of a rock that is produced by back water effect and wake of flow.

(c) Bearing effect of small stones under a big rock.

The influence of the above (a) is conceivable to be attributed to decrease of the difference in density of the fluid and the stone and change of viscosity of the fluid and the current velocity, both of which render a change to the transfer of a rock. The influence of the above (b) can naturally be perceived when the water depth comes to be less than the diameter of a rock. Though the actual effect of the above is unknown (c), it would be necessary to investigate the possibility in examining the transfer of a big rock. In this paper, efforts will be made to find how muck the above two influences (a) and (b) act on transfer of a rock through the critical condition for the movement.

4.1 Critical Tractive Force for Gravels in Mud Flow.

1) Condition of equilibrium of the gravel in a mud flow.

The critical tractive velocity of gravel placed in a fluid containing an abundance of sediments would be different from that of gravel of the same size in lucid streams due to decreased difference in density between the fluid and the gravel, increased viscosity of the fluid, or change of current velocity. This difference would be traced in the stream containing an abundance of clayey particles in which such a difference would be assumed to present itself most conspicously.

Regarding the critical tractive force of a gravel grain in lucid fluid, C. M. White[14], Kurihara[15], Iwagaki[16] and Tsuchiya[17] have been working on theoretical analysis since A. Shields discovered that it could be manifested by the Reynolds Number $U_c^* D/\nu$ that was formulated with critical tractive velocity and sediment diameter. In this instance, there are two ways of analysis based on the theoretical approach of the subject. As White and Kurihara contend, the value obtained by dividing the shearing force acting on a unit area by the number of the projected grain per unit area is accepted as the value of equilibrium each grain holds, and as Iwagaki and Tsuchiya explain, each grain on the bottom bears the fluid resistance acting on it and the resistance resulting from pressure gradient.

As there is no fundamental difference between the mechanism of transfer of a gravel grain in a mud stream and that in a lucid stream, an examination is being made on critical tractive force according to Iwagaki's idea.

a) Equilibrium in laminar sublayer.

Supposing, as is shown in Fig. 4.1, there is a gravel grain of the diameter D on a rough bed, the condition to move the grain may be dealt with. Taking the fluid resistance R_T and the gravity of a grain as the force acting on gravel grains, and also, taking the frictional angle of a grain ϕ and the gradient of the rough bed, the equilibrium of the forces acting on a grain would be expressed as follows:

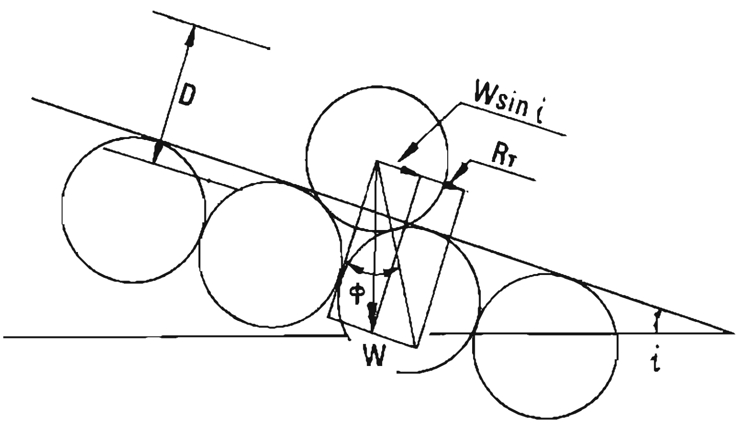

Fig. 4.1 Force acting on a spherical gravel grain

$$R_T + W\sin i = W\cos i \cdot \tan\phi \tag{4. (1)}$$

then taking σ and ρ_s for the density of gravel and fluid and C_D for the drag coef,.

$$R_T = (\rho_s/8)C_D u^2 \pi D^2 \tag{2}$$

$$W = (\sigma - \rho_s)g(\pi/6)D^3 \tag{3}$$

Hence, Eq. (1) is

$$\{(\sigma-\rho_s)g(\pi/6)D^3\}\cos i(\tan\phi-\tan i)=\frac{\rho_s}{8}C_D u^2\pi D^2 \tag{4}$$

The equilibrium condition is consistent with any fluid. A stream containing clayey particles has the nature of Bingham fluid. The velocity distribution in two-dimensional laminar flow is expressed as follows:[18]

$$u=(u_* z/\nu_B)\{a'-(z/h)\} \tag{5}$$

Where u_* is tractive force, ν_B plastic specific viscosity $(=\mu_B/\rho_s)$, $a'=z_y/h$, z_y the height at the point where τ_y appears, h water depth, τ_y is yield shear stress of fluid, μ_B and τ_y are expressed in the following equations:[19]

$$\mu_B=\mu_c\{1+3/(1/\phi-1/\phi_{Fc})\} \tag{6}$$

$$\tau_y=A_1(\phi_F-\phi_{F0})^3+A_2\phi_F^2 \tag{7}$$

Where ϕ_F is floc volume fraction of clayey particles and ϕ_s clay volume fraction, there is a relation of $\phi_F=C_{Fs}\phi_s$. C_{Fs} has no relation with fraction, but coef. changeable according to the electrochemical nature of soil. ϕ_{Fc} is maximum packed floc volume fraction, ϕ_{F0} constant floc volume fraction below which $\tau_y=0$. A_1 and A_2 constants.

When the diameter of a gravel grain is smaller than the water depth, the current velocity of the height from the bottom is expressed by

$$u=(u_*^2 D/\nu_B)a' \tag{8}$$

Inserting the expressions for u into Eq, (4)

$$u_{*c}^2 a'^2/[\{(\sigma-\rho_s)/\rho_s\}gD\tan\phi]=1/\{(3/4)C_D(u_* D/\nu_B)^2\} \tag{9}$$

The drag coef. C_D acting on the particles contained in Bingham fluid is that given in Fig. 4.2. The Reynolds Number R_e^* used to represent C_D in Fig. 4.2 is expressed by Itoh as follows:[20]

$$R_e^*=R_e/(1+N_y I_D) \tag{10}$$

then, $R_e=uD/\nu_B$, $N_y=\tau_y D/\mu_B u$, $I_D=I_A/I_B$

$$I_A=\iiint\frac{1}{A_1^2}\,dx\cdot dr\cdot dz$$

$$1/A_1=\sqrt{2(\dot e_{xx}^2+\dot e_{yy}^2+\dot e_{zz}^2)+\dot e_{yz}^2+\dot e_{zx}^2+\dot e_{xy}^2}$$

They are all dimensionless, X, Y, Z, for the length, $\dot e_{xx}$ and $\dot e_{xy}$ for the rate of strain e_{xx} and e_{xy}. As, however, I_D cannot be calculated for the present, it is given experimentally in Fig. 4.3.
Hence,

$$R_e=uD/\nu_B=(u_{*c}D/\nu_B)^2 a' \tag{11}$$

$$N_y=(\tau_y/\tau_{0c})(\rho_s u_{*c}^2/\mu_B u)=(1/a')-1 \tag{12}$$

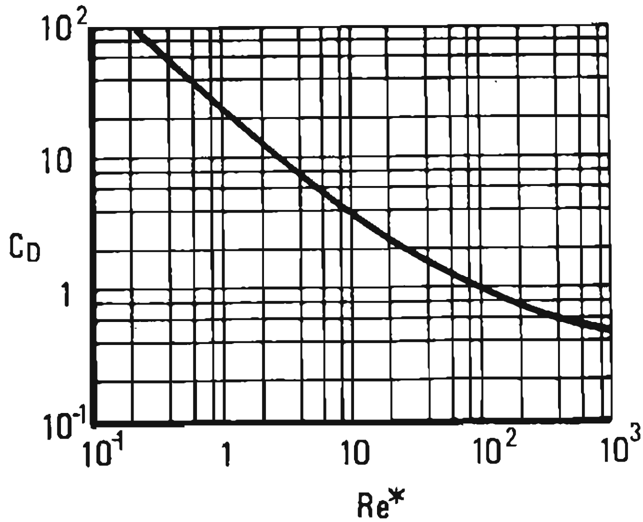

Fig. 4.2 Relation between C_D of sphere in mud stream and Modified Reynolds Number (by Itoh)

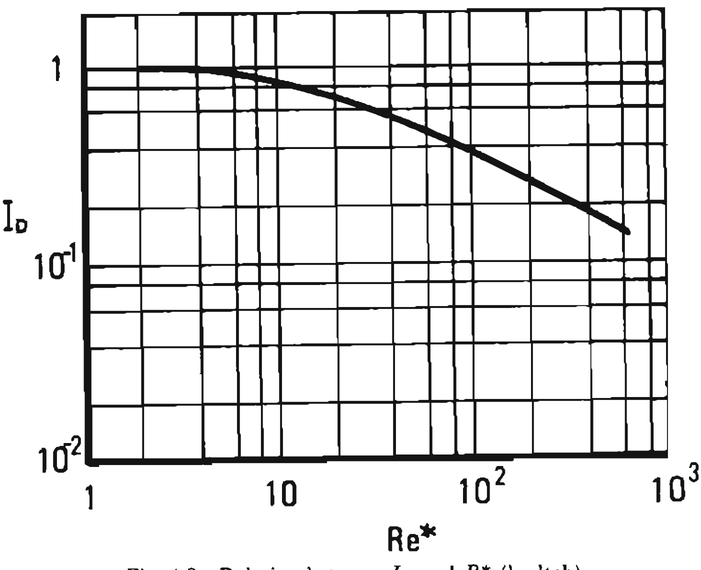

Fig. 4.3 Relation between I_D and R_e^* (by Itoh)

then, transmitted to

$$R_e^* = (u_{*c}D/\nu_B)^2 a' / [1 + \{(1/a') - 1\} I_D] \tag{13}$$

R_e^* is obtained by giving a' and $u_{*c}D/\nu_B$. so that the (13) formula can be calculated. As a result the relation of $u_{*c}^{*2}/\{(\sigma/\rho)-1\}gD\tan\phi$ and $U_{*c}D/\nu$, which was presented by Shields, is shown with a' as parameta. However, to show on a figure the phenomenon presented by fluids of different natures, it is desirable to represent them with a magnitude to satisfy the mechanical similitude of such phenomenon. In this case, it is considered to use the equation (13). From this the following equation is obtained.

$$\frac{u_{*c}^2 a' \left\{1+\left(\frac{1}{a'}-1\right)I_D\right\}}{\frac{\sigma}{\rho_s} gD\tan\phi} = \frac{1}{\psi\left[\frac{u_{*c}D}{\nu_B}\left\{\frac{a'}{1+\left(\frac{1}{a'}-1\right)I_D}\right\}^{1/2}\right]}$$

$$\psi\left[\frac{u_{*c}D}{\nu_B}\left\{\frac{a'}{1+\left(\frac{1}{a'}-1\right)I_D}\right\}^{1/2}\right] = \frac{3}{4} C_D\left(\frac{u_{*c}D}{\nu_B}\right)^2 \frac{a'}{1+\left(\frac{1}{a'}-1\right)I_D} \tag{14}$$

In this new coordinate axis, as shown in Fig. 4.4, it coincides with the relation of the preceding representation of $a'=1$ (corresponding to Newtonian fluid) and can be made into a relation irrespective of the value of a'. Needless to say, the above relation is consistent only within the sphere of laminar flow.

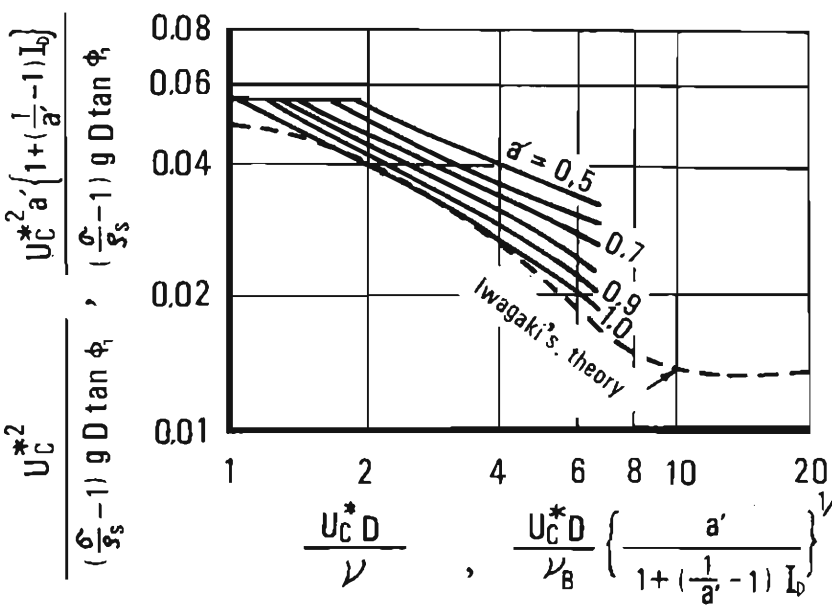

Fig. 4.4 Dimensionless expression of critical tractive force in mud stream

b) Equilbrium condition in turbulent flow.

It is defficult at present to deal theoretically with the problem of a gravel grain protruding out of the laminar flow and receiving a resistance by turbulence, as the phenomenon of the turbulence of plastic flow is yet to be elucidated. However, in treating non-Newtonian fluid, not infrequintly is it engineeringly satisfactory to treat it in just the same way as Newtonian fluid with a dynamic magnitude, even in the area of turbulent flow when the relation among the new dynamic similitudes found with a certain standard taken with a proper dynamic magnitude in the laminar flow shows a coinciding relation to that in the Newtonian flow. If the relative magnitudes can be decided at the point of laminar flow in this problem, satisfactory arrangement of experimental results might be obtainable.

2) Experiment relating critical tractive force. (Critical tractive force will hereafter be referred to as "C.T.F.")

The result of the experiment is shown in Fig. 4.5. using dimensionless function of C. T. F. In Fig. 4.5 is shown Iwagaki's theory relating the value a'=1, and its experiment. Taking 0.3 for the shadow coef., the measured value coincides to the Iwagaki's experimental equation when regulated with the dimensionless function of the critical force. Also, Fig. 6 shows the value measured with the grains placed upon similar grains fixed on the fixed bed. The result of comparison made between the C. T. F. and the theoretical value of Iwagaki and Tsuchiya is shown in Fig. 4.6.

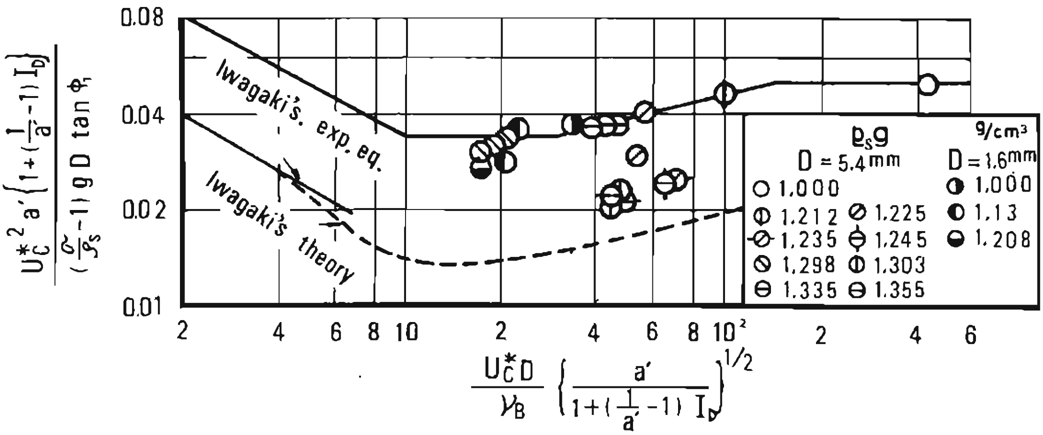

Fig. 4.5 Experimental value expressed by dimensionless function of C. T. F.

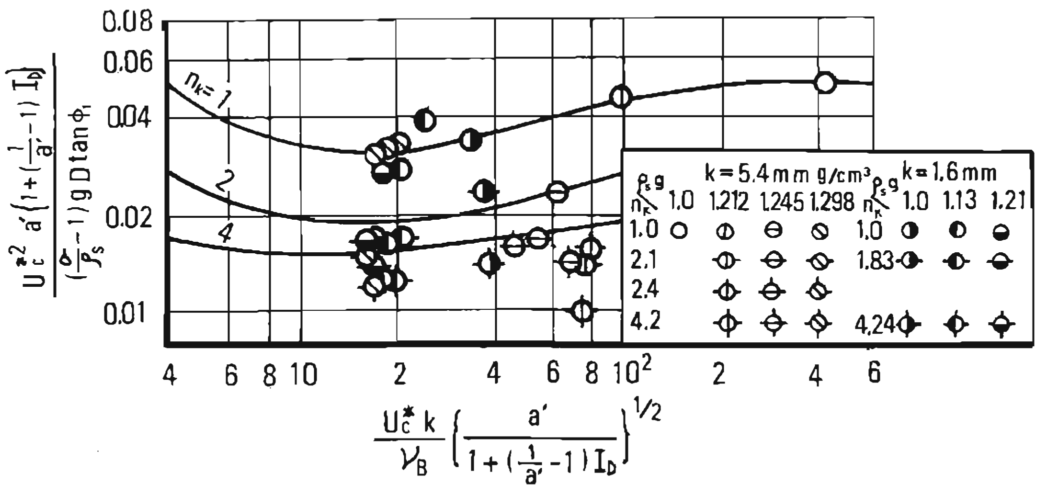

Fig. 4.6 Result of experiment of spherical grains of the diameter K placed on a fixed bed

The mark η_K indicates the ratio of the diameter of the grain fixed at the bed to that of the one placed upon it. As the degree of scattering of an experimental value is about the same as in the case of a′=1.0, the dimensionless function of C. T. F. used here can be said to be adequate in representing the force acting on a gravel grain.

3) Experiment formula.

The experiment formulas made on the basis of the above experiments are as shown below against the limits of the experiment made.

$$671 \leqq R_* \quad u_{*c}^2 = 0.05\left\{\left(\frac{\sigma}{\rho_s}\right)-1\right\} gDa'^{-1}\left\{1+\left(\frac{1}{a'}-1\right)I_D\right\}^{-1}$$

$$162.7 \leqq R_* \leqq 671$$

$$u_{*c}^2 = \left[0.015 g\left\{\left(\frac{\sigma}{\rho}\right)-1\right\}\right]^{25/22} \cdot D^{31/22} \cdot \nu_B^{-(3/11)} \cdot a'\left\{1+\left(\frac{1}{a'}-1\right)I_D\right\}^{-(7/5.5)}$$

$$54.2 \leqq R_* \leqq 162.7 \quad u_{*c}^2 = 0.034\left\{\left(\frac{\sigma}{\rho}\right)-1\right\} gDa'^{-1}\left\{1+\left(\frac{1}{a'}-1\right)I_D\right\}^{-1}$$

but $$R_* = \left\{\left(\frac{\sigma}{\rho}\right)-1\right\}^{1/2} \cdot g^{1/2} \cdot D^{3/2} \cdot \nu_B^{-1}\left[a'\left\{1+\left(\frac{1}{a'}-1\right)I_D\right\}\right]^{-(1/2)} \tag{15}$$

As R_* contains the nature of fluid and the forces of stream, it requires a number of trial calculations, but u_{*c} is obtainable. For a gravel grain placed on an inclined plane, the product of the formula u_{*c} of the (15) divided by $\cos i(\tan\phi-\tan i)/\tan\phi$ is applicable. Where the object is a big stone, the topmost one of the (15) formulas is applicable, but, where a Reynolds Number is large, it would make $I_D=0$, so the (15) formula would come to be expressed by $u_{*c}^2=0.05\{(\sigma/\rho_s)-1\}gDa'^{-1}$. The corresponding one for Iwagaki being $u_{c*}^2=0.05\{(\sigma/\rho)-1\}gD$, the critical tractive velocity of the stone in a mud stream is that obtained by multiplying the critical tractive velocity in a lucid stream by $\{(\sigma/\rho_s)-1\}/a'\{(\sigma/\rho)-1\}$.

4.2. Critical condition of rolling for a rock when there is a difference in water levels on both sides of a rock

At the narrow part of a valley a rock protruding from the bed of a stream decreases the stream cross area which, accompanying back water effect of stream, would intensify the wake of the stream as the current velocity gains, and this would enlarge the difference in the water levels on both sides of the rock. The force acting on a rock in such a stream condition is assumed to be bigger when compared with that in a uniform flow. There have been many cases in which the transfer of big stones were found to have taken place in water depths less than the diameter of the stone. The relative effects are being examined.

1) Forces acting on a big stone.

The stream around a rock is simplified as shown in Fig. 4.7. The forces acting on a gravel grain are drag force, uplift by stream and hydrostatic pressure caused by the difference in the water levels at both sides of the grain.

(a) Hydrostatic pressure. Taking the depths of water at both sides of a rock to be indicated by $\varepsilon_1 D$ and $\varepsilon_2 D$, and assuming the rock to be of spherical shape, the dif-

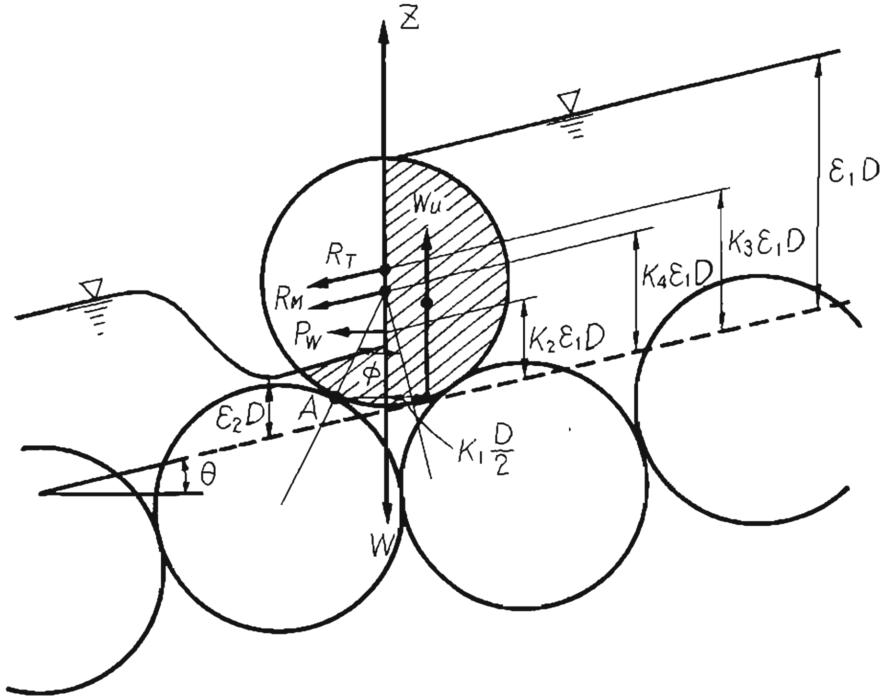

Fig. 4.7 Forces acting on gravel grains and their directions

ference of the pressures is

$$P_i=\rho g\int_0^{\varepsilon_i D} b(\varepsilon_i D-z)dz=\rho g\beta_i(\pi D^3/8)$$

$$\beta_i=\left(\varepsilon_i-\frac{1}{2}\right)\left[1+\frac{8}{\pi}\left\{\left(\varepsilon_i-\frac{1}{2}\right)\sqrt{k_i}+\frac{1}{4}\sin^{-1}\left(\varepsilon_i-\frac{1}{2}\right)\right\}\right]+\frac{2}{3}\frac{8}{\pi}\sqrt{k_i^3}$$

$$k_i=\frac{1}{4}-\left(\varepsilon_i-\frac{1}{2}\right)^2$$

Hence, $$\Delta p=\rho g\lambda(\pi D^3/8),\quad \lambda=\beta_1-\beta_2 \tag{16}$$

the height of acting point $Z_{\Delta p}$ is

$$Z_{\Delta p}=(P_1Z_{pw_1}-P_2Z_{pw_2})/\Delta P=k_2\varepsilon_1 D$$

$$P_iZ_{pw_i}=\int_0^{\varepsilon_i D} PZdZ=\rho g\Lambda(5\pi D^4/64) \tag{17}$$

The value of Λ is shown in Fig. 4.8. The difference of the acting force is horizontal.

(b) Drag force. Taking into consideration a stream checked by a rock and the momentum in a stream being decreased, and taking u for the current velocity b for the width of the rock at its height Z, then the force of a stream acting on a rock may be shown as follows:

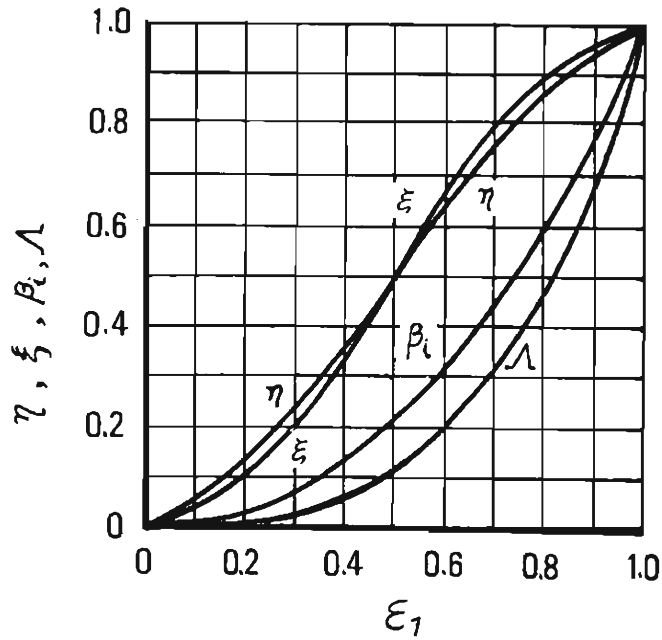

Fig. 4.8 Relation between η, ξ, β_i, Λ and ε_1

$$R_T = \frac{\rho}{2}\int_0^{\varepsilon_1 D} C_D u^2 b\, dZ \tag{18}$$

C_D is the drag coefficient, $\varepsilon_1 D$ is the depth of the stream. The current velocity around an obstacle protruding from a river bed is complicated, and the vertical flow must also be taken into account. Taking the average for the formula (18), we have

$$R_T = \frac{\rho}{2}\, C_D(\eta-\zeta)\zeta(\pi D^2/4)u_m^2 \tag{19}$$

ζ is the ratio of the downstream projected area of the rock shilded by other gravel grains. $\eta\pi D^2/4$ is the downstream projected area at the depth of water εD. The average velocity u_m is expressed by

$$U_m = A_* U_* \tag{20}$$

A_* is for magnitude relating the water depth and the degree of roughness, and u^* for tractive force. Acting point of this force, in view of indistinct distrubution, is set from the stream bed as

$$Z_{R_T} = K_3 \varepsilon_1 D \tag{21}$$

K_3 is a coefficient. The acting direction runs parallel with the stream bed.

(c) Virtual mass force. The accelaration force of a stream is indicated as follows:

$$R_M = \rho C_M M'(t) du/dt \tag{22}$$

C_M is virtual mass coef. $M'(t)$ the submerged volume of a rock. The force in a state where the stream just in front of a rock creates a back water effect to the rock might be allowed to be represented as under, where the friction gradient can be omitted and an accelaration term for rectangular section given as follows:

$$\frac{dU}{dt}=-\left\{\frac{2}{3}-\frac{1}{2}\frac{h}{\left(i-\frac{\partial h}{\partial x}\right)}\frac{\partial^2 h}{\partial x^2}\right\}-\frac{\partial h}{\partial x}\frac{1}{U_m} \tag{23}$$

Submerged volume $M'(t)$ at any time can be given by

$$M'(t)=M'_0+(\partial h/\partial t)\Delta t\eta_w(\pi D^2/4)=\Gamma(\pi D^3/6),\quad \Gamma=\left(\xi_0+\frac{3}{2}\frac{\partial h}{\partial t}\Delta t\eta_w\right)$$

M_0' is the submerged volume at the initial time. η_w is section area coef. of a rock cut at the emerged surface at the M_0'. ξ_0 is the ratio of M_0' to the whole volume of the rock D. Therefore, R_M will be developed into the following formula by applying the formula (23), to

$$R_M=\rho C_M\Gamma(\pi D^3/6)(du/dt) \tag{24}$$

The point of action of this force is adequately considered to act at the center of M', in view of the complexity of the velocity distribution. From the river bed, this is represented as

$$Z_{R_M}=K_4\varepsilon_1 D \tag{25}$$

The direction of the action is in parallel to the river bed. Uplift is neglected when considering a rock too large compared with the velocity gradient.

2) Critical condition of rolling.

Stability is required for rolling, with a stone object placed on spherical grains evenly arranged in a row as shown in Fig. 4.7. The average gradient of the grains in a row is indicated by θ, and having ϕ for the angle made at the center of the grain by the normal direction of the river bed and the direction of the point A. The moment around point A is as follows:

Table 4.1. Magnitude of power around point A and its arm length.

		Magnitude	arm length		
Weight of a grain	W	$\sigma g(\pi D^3/6)$	$(D/2)\sin(\phi-\theta)$		$-$
Buoyancy of a grain	Wu	$\rho g\xi(\pi D^3/6)$	$(D/2)\{\sin(\phi-\theta)+\alpha_1\}$	$\alpha_1=K_1$	$+$
Hydrostatic Pressure	Pw	$\rho g\xi(\pi D^3/6)$	$(D/2)\{\cos(\phi-\theta)-\alpha_2\}$	$\alpha_2=1-2K_2\varepsilon_1$	$+$
Hydrodynamic Pressure	Rt	$(\rho/2)C_D(\eta-\zeta)U_m^2(\pi D^2/4)$	$(D/2)\{\cos\phi+\alpha_3\}$	$\alpha_3=2K_3\varepsilon_1\cos\theta-1$	$+$
Virtual Mass Force	Rm	$\rho C_M\Gamma(du/dt)(\pi D^3/6)$	$(D/2)\{\cos\phi+\alpha_4\}$	$\alpha_4=2K_4\varepsilon_1\cos\theta-1$	$+$

$$\frac{C_D}{2}(\eta-\zeta)A_*^2U_*^2(\cos\phi+\alpha_3)-\frac{2}{3}\frac{\sigma}{\rho}gD\sin(\phi-\theta)$$

$$-\frac{2}{3}\xi gD\{\sin(\phi-\theta)+\alpha_1\}-\frac{1}{2}gD\lambda\{\cos(\phi-\theta)-\alpha_2\}$$

$$-\frac{2}{3}C_M(du/dt)\Gamma(\cos\phi+\alpha_4)=0 \tag{27}$$

Replacing the above formula with $u_*^2=g\varepsilon_1 D\sin\theta$, the formula obtained is

$$\varepsilon_1=\frac{\frac{2}{3}\frac{\sigma}{\rho}\sin(\phi-\theta)-\frac{2}{3}\xi\{\sin(\phi-\theta)+\alpha_1\}-\frac{1}{2}\eta\{\cos(\phi-\theta)-\alpha_2\}-\frac{2}{3}\frac{C_M}{g}\Gamma\frac{du}{dt}(\cos\phi+\alpha_4)}{\frac{C_D}{2}(\eta-\zeta)A_*^2\sin\theta(\cos\phi+\alpha_3)} \tag{28}$$

The above equation shows the ratio of depth to grain-size for a critical condition of rolling when C_D has no relation with the diameter of rock.

3) Results of experiment

With a glass ball, a spherical stone or a steel ball, each placed at the concave made in the fixed bed, the hydraulic force is measured when a ball rolls in steady flow. The magnitude of each term of the equation (28) and the drag coef. are obtained. For the drag coef. of a body, part of which is exposed avobe water level, the drag coef. of a body having no wave resistance at water surface is applicable.

5. Conclusion

In this report, the real condition of mud-debris flow has been investigated by means of on the spot research and the study of past records, both of which have been arranged accordingly. According to the causes supplying sediments to the place of flowing water, the classification of mud-debris flow were made into the following: Attributable to volcanic eruption, to fall from a steep slope in a valley side, to the flow of deposit in a valley and to landslide.

In this research, it seems that there are many cases in which the so-called "mud-debris flow" would rather properly be called "mud flow" and the transfer of huge stones is a collateral phenomenon attending mud flow.

The requirement in studying the occurrence of a mud-debris flow is the prediction of the place, time and scale of the occurence. This report has dealt with the presumption of the place causing mud-debris flow due to movement of deposits in a valley by means of topographical research. It showed that the mud-debris flow means that the deposits that have accumulated by the action of mass force but which have not hitherto been acted upon by stream are transferred by the action of the surface stream to an aqueus gradient.

The sediment discharge in a valley under heavy rain is bigger than expected, especially the transfer of large rocks in streams of a depth of water less than the sizes of the rocks. This paper has studied, from among a number of elements conductive to the transfer of sediments, the influence of the abundant component of clayey particles in a stream and the influence of the difference in water level at both sides (up-and-down stream) of a rock which is attended with back water effect and wake to examine the influence of each of these two factors at the critical condition of movement.

In the former influence, an arrangement has been made from the result of experi-

Table 4.2. Magnitude ov each moment of the critical condition of movement

0	$h_1$cm	$h_2$cm	Z_0cm	ε_1	ε_2	$(2/3)(\sigma/\rho) \times \sin(\phi-\theta)$	$(2/3)\xi \times \{\sin(\phi-\theta)-\alpha_1\}$	$(1/2)\eta \times \{\cos(\phi-\theta)-\alpha_2\}$	$(C_D/2)(\eta-\zeta)A_*^2 \times \sin\theta(\cos\phi+\alpha_3)$	C_D
glass ball		$D=3.09$		$\sigma/\rho=2.441$			$\tan\phi=0.315$			
0.0193	1.995	0.865	0.713	0.876	0.511	0.459	0.195	0.212	0.0514	0.92
0.0263	1.675	0.545	0.713	0.773	0.407	0.447	0.177	0.210	0.0609	0.5708
spherical stone		$D=4.61$		$\sigma/\rho=2.608$			$\tan\phi=0.235$			
0.0193	3.325	1.285	0.665	0.864	0.643	0.365	0.169	0.153	0.0435	1.0
0.0263	3.185	1.235	0.665	0.833	0.630	0.345	0.136	0.141	0.0389	1.0
steel ball		$D=3.20$		$\sigma/\rho=7.741$			$\tan\phi=0.318$			
0.0628	2.38	3.135	0.62	1.142	1.234	1.25	0.161	0	1.089	1.05
0.0927	1.19	0.30	0.62	0.650	0.345	1.10	0.197	0.129	0.773	1.19
steel ball		$D=3.97$		$\sigma/\rho=7.783$			$\tan\phi=0.256$			
0.0628	2.385	1.485	0.69	0.775	0.548	0.969	0.129	0.018	0.535	1.07
0.0927	1.80	0.670	0.69	0.627	0.347	0.817	0.164	0.116	0.537	1.25
steel ball		$D=5.08$		$\sigma/\phi=7.194$			$\tan\rho=0.213$			
0.0628	3.715	1.705	0.77	0.777	0.487	0.762	0.120	0.189	0.452	1.07
0.0927	2.310	1.40	0.77	0.577	0.390	0.608	0.114	0.073	0.422	1.44

ments by dimensionless expression of the critical tractive force with the addition of the plastic property born by a clayey stream, and has been completed in the same from as in the critical tractive force in the case of a lucid stream.

In cases of the latter influence, the result of the critical condition obtained from the rolling of a spherical rock placed in a stream dedth which is less than the size of a rock, has been taken into consideration when explaining the rolling of a large rock in a natural valley. Other factors taken into condideration as causes of the rolling of a large rock are the force acting around the rock's fulcrum and hydrostatic pressure born by the difference in the depth at both sides of the rock. The result of the consideration is shown in the equation (28).

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